Influence of the Large-Scale Circulation Anomalies on the Genesis, Trajectory and Potentiality of the Tropical Cyclones in the Bay of Bngal Region

Ph. D. Synopsis

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Declaration

I hereby declare that this thesis contains original research work carried out by me under the guidance of Prof. Soumendu Chatterjee, Professor and Head, Department of Geography, Presidency University, Kolkata, India as part of the PhD programme.

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

I also declare that; this work has not been submitted for any degree either in part or in full to any other Institute or University before.

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Certificate

This is to certify that the thesis entitled "Influence of the Large-Scale Circulation Anomalies on the Genesis, Trajectory and Potentiality of the Tropical Cyclones in the Bay of Bengal Region" submitted by Shri Abhisek Pal, Registration Number R-17RS12110083 and date of registration 8th December, 2017, in partial fulfilment of the requirements of the award of "Doctor of Philosophy", is a record of bonafide research work carried out by him under my supervision.

Neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

Signature of the Supervisor with date and official stamp

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1. Introduction

Tropical cyclones (TCs) are world's one of the most devastating natural phenomena causing enormous loss of lives and property damages. The 1970 Bangladesh cyclone killed nearly 3 lakh people. The 1999 Odisha TC caused near about ten thousand human deaths. Recently due to advanced TC forecasting and rapid evacuation programs, the death toll has been greatly reduced but the economic losses are ever increasing. The 2013 ESCS *Phailin* caused an economic damage of INR 89020 million and 2020 SuCS *Amphan* caused a loss of over one billion Indian rupees. TCs typically develop over the warm sea surfaces and maintained by the energy transfer from the sea surface to the atmospheric boundary layer. Gray (1975) first summarized the key environmental parameters essential for TC genesis such as SST, tropospheric θ_e gradient, lower tropospheric relative vorticity, mid-tropospheric relative humidity and Coriolis parameter. The Maximum Potential Intensity (MPI) theory of Emanuel (1986) hypothesized TCs as an ideal Carnot heat engine drawing energy from the thermodynamic disequilibrium between the sea surface and atmospheric boundary layer. TC genesis tends to occur in the regions of increased air-sea humidity difference and positive latent heat flux anomalies associated with warm state years over the western North Pacific (Zhou et al. 2015). Positive SST anomalies over the tropical Pacific lead to the formation of stronger low-level winds and enhanced convection (Huangfu et al. 2017). More than 75% of the total TCs in the western north Pacific occur when the vertical shear is below 20 m s^{-1} and there is an anti-cyclonic circulation exists in the upper troposphere during the formation of the TCs (Yoshida and Ishikawa, 2013). Kaplan and DeMaria (2003), Kaplan et al. (2010) emphasized on the importance of mid-tropospheric relative humidity on TC intensification and noted that comparatively higher values of relative humidity is essential of the rapid intensification of TCs.

TCs typically act like a protected symmetric vortex in a fluid flow that is uniform and non-interacting. The movement of TCs are primarily directed by the advection of relative vorticity. The large relative vorticity concentrated at the center is advected by the large-scale wind circulation patterns surrounding the TC. TC motion is closely related to the surrounding wind and height fields (Miller and Moore, 1959; George and Gray, 1976; Chan, 1985; Zhou et al., 2018). George and Gray (1976) demonstrated that TCs tend to recurve when positive zonal winds are present in the upper troposphere specifically at 200 hPa in the 8-20 degrees pole-ward to the TC center. Gentry (1983) showed that 80% of the TCs move eastward from the west when north-west and westerly zonal winds are greater than 20 m s^{-1} at 1500-2000 km from the center.

TC MPI is defined as the maximum achievable intensity of a TC in a given thermodynamic environment. Emanuel (1986), Bister and Emanuel (1998) demonstrated an MPI theory (hereafter EMPI) based on macroscopic thermodynamic processes. Tonkin et al. (2000), Free et al. (2004) found EMPI to be very efficient in estimating the maximum intensity of real TCs over the Pacific and Atlantic oceans. However, DeMaria and Kaplan (1994) revealed that on average TCs reach only 55% of their theoretical EMPIs and only 20% TCs reach more than 80% of their EMPIs in the Atlantic. Yoshida and Ishikawa (2013) noted that TC genesis does not occur where vertical wind shear is over 20 m s^{-1}, whereas Zehr (1992) identified the threshold value for TC genesis is 15 m s^{-1} over the western-north Pacific. Numerical model simulations performed by Frank and Ritchie (2001) noted that 15 m s^{-1} vertical wind shear can diminish an intense TC within 24 hours.

Meteorologists are quite certain that the global climate is changing with a warming trend (Foster and Rahmstorf, 2011; Wu et al., 2011). The global surface temperature is increased by 0.85°C over the period 1880-2012 and the sea surface temperature (SST) is increased at a rate of 0.11°C per decade over the period 1971-2010 (IPCC, 2013). Considering the environmental influence on TCs, it is no surprise that any changes to the environmental factors will eventually impact the overall character of the TCs. Emanuel (2005) concluded that TC intensity has already changed in terms of increase in TC power dissipation index (PDI) in the north Atlantic. An increase in TC intensity is also noted by Elsner et al. (2008); Kossin et al. (2013) in the Atlantic and western North Pacific, however global change in TC intensity is not significant. Furthermore, numerical simulations performed by Knutson et al. (2008); Knutson and Tuleya (2004); Yu and Wang (2009); and Bhatia et al. (2018) noted an increase TC intensity under a warmer environment. The increase in TC intensification is mainly attributed to the increase in ocean heat content (Liu et al., 2016). However, conflicting results (decrease in TC frequency) are documented by Li et al. (2007), Sugi and Yoshimura (2012), and Tory et al. (2013) in the Atlantic and western North Pacific. The physical process behind such reduction in TC frequency is still uncertain (Knutson er al., 2020). Sugi and Yoshimura (2012), Sugi et al. (2015) identified reduced upward mass flux as one of the main factors for reduced TC frequency. Global circulation models (GCMs) are considered as a major tool in climate research. The outputs of such models help us to understand changes in climate at both global and regional scales (Bannister et al. 2017). World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) is one of the major contributors in climate change research which is currently in its sixth phase (CMIP6). The

CMIP6 is significantly improved in terms of physical parameterization and spatial resolution compared to the earlier versions (Eyring et al. 2016; 2019).

The present study has been focused on the entire BoB region situated in the northern part of the Indian Ocean. The triangular-shaped BoB is the largest bay in the world covering an area of approximately 2,172 thousand square km. The latitudinal area of the BoB extends between 5-22.5 degrees north and the longitudinal area extends between 80-100 degrees east.

The main objectives of the thesis are as follows

1. To examine the seasonal variability in the environmental factors and their influence on TC genesis patterns.
2. To characterize TC track patterns and identification of the factors determining them.
3. To assess the environmental dynamical control on the maximum potential intensity of TCs.
4. To measure the recent trends in TC intensity parameters and assessment of maximum potential intensity under the present and future climates.
5. To assess the probable changes in the thermodynamic and kinematic structure of TCs under the future projected climates.

2. Influence of seasonal variability in the environmental factors on TC genesis

This chapter addressed the first objective. It examined the seasonal variability in in the environmental factors and their influence on variability in TC genesis. Moreover, it assessed the relative contribution of the environmental factors on the observed seasonally variable nature of the TCs. An index named Genesis Potential Index (GPI) has been introduced to examine the variability in the environmental factors. The GPI is expressed as:

$$GPI = \{Inst + Rhum + SST + Rvor + (1 - MSLP) + (1 - Vshear)\}$$

Where, Inst is instability parameter which is represented by the temperature difference between 850 and 500 hPa (Nath et al. 2013), Rhum is the relative humidity at 600 hPa, SST is the sea surface temperature, Rvor is the relative vorticity at 850 hPa, MSLP is the mean sea level pressure and Vshear is the vertical wind shear between 850 and 200 hPa levels. This study has followed min-max normalization (Han et al. 2012) method to transform the variables within the range 0 to 1. The monthly mean relative vorticity at 850 hPa data and the SST data were obtained from ECMWF ERA-Interim dataset (Dee et al. 2011) with spatial resolution of 2.5 degrees. Monthly mean MSLP, air temperature at 500 and 850 hPa, relative

humidity at 600 hPa and u- and v-wind components at 200 and 850 hPa level were collected from NCEP-DOE AMIP-II Reanalysis 2 dataset (kanamitsu et al. 2002) with a spatial resolution of 2.5 degrees. The TC best track dataset was collected from the best track data of the RSMC, New Delhi with intensity >17 kts.

The results of this chapter suggested that the large-scale environments showed a significant amount of seasonal variability which were reflected in the overall seasonal character of the TC genesis. It was observed the that mean TC genesis locations were shifted southward from the month of July to December. The calculated GPI successfully captured the seasonal shifting of the TC genesis locations. It was observed that the frequency of TC genesis was very low during the SW monsoon period compared to the post-monsoon, however, the SW monsoon scored higher GPI compared to post-monsoon. The higher GPI value during the SW monsoon period was contributed by favorable conditions of relative humidity, SST and instability, and MSLP but TC genesis was restricted due to very high vertical wind shear and lower relative vorticity. In the post-monsoon season, however very low vertical wind shear and increased relative vorticity overcame the effect of lower humidity and instability favored TC genesis.

3. The influence of surrounding winds on TC movement

This chapter focused on the second objective. This chapter aimed to the track pattern classification and identification of the appropriate steering level that determine the movements of the TCs over the BoB region. TC tracks were classified into four distinct classes such as straight-moving, recurving, northeast (NE) moving, and other tracks. Straight-moving TCs were those which headed between 250° and 360° during their initial and final 24 hrs (Miller et al. 1988; Chen et al. 2009); whereas, the TCs which initially moved north-westward and then changed their paths to north-eastward were termed as recurving tracks. The TCs whose general direction of movement remained constant throughout their life with heading towards northeast were named NE moving tracks. The TCs which did not fit into any of the above-mentioned classes were termed as other tracks. Wind flow patterns at the 200 hPa level were used to determine whether distinct wind circulation patterns existed for different types of TC track patterns. A TC track prediction scheme has been presented to examine the effectiveness of using the 200 hPa level surrounding winds to estimate the probable track of a TC. An index named Cyclone Translation index (CTI) has been formulated to estimate the probable track of a TC. The CTI is defined as:

$$CTI = -(WD \times .7) + (P24 \times .15) + (ARV \times .15)$$

Where, WD is the angular difference in degrees between the mean 200 hPa winds at 5° radius and the center of the surrounding grid points from the TC center, P24 is the sea level pressure fall during last 24hrs and ARV is the advection of relative vorticity at 850 hPa. The 6-hourly daily and monthly u and v wind components at 200, 700 and 850 hPa levels, surface level pressure was collected from the ERA5 global reanalysis (Hersbach et al. 2020) dataset with a spatial resolution of 0.25 degrees. 6-hourly TC best track datasets over the BoB region for the period from 1981 to 2015 were obtained from the U.S. Navy's JTWC.

The results of this chapter revealed that out of the total of 67, October, November, and December accounted for 29, 23, and 15 TCs respectively. In the month of October, 18 TCs were straight-moving, 8 were recurving and 2 were NE moving TCs. In November, 15 were straight-moving, 7 were recurving and 2 were NE moving TCs. And lastly, in December, the number of straight-moving, recurving, and NE moving TCs were 8, 5, and 1 respectively. The monthly mean wind circulation patterns at 200 hPa over the southern part of the BoB was mostly dominated by strong easterly winds whereas the northern part was dominated by westerlies and the entire wind system migrated southward from October to December. The mean wind circulation patterns during the straight moving and recurving TCs were very similar to the overall monthly wind flow patterns. It was observed that straight moving TCs acquired their northwest-ward movement due to the presence of the strong easterly winds and they have ended their life cycle before entering into the mid-latitude westerly winds, whereas, the recurving TCs significantly moved further northward and came under the influence of mid-latitude westerlies and recurved northeast ward. The CTI predicted TC tracks quite efficiently. The direct positional error showed an average error of 105.9, 66.7, and 52.8 km for the lead times of km 24, 12, and 6 hrs respectively.

4. Influence of vertical wind shear on the maximum potential intensity of TCs

This chapter addressed the objective three which analyzed the seasonal variability maximum potential intensity of TCs. Furthermore, this chapter also focused on the assessment of vertical wind shear control on the maximum potentiality of BoB TCs. The EMPI is expressed as:

$$V_{pot}^2 = \frac{C_k}{C_d}\frac{T_s - T_0}{T_0}(h_0^* - h^*)$$

Where V_{pot} is the maximum 10m wind speed, C_k and C_d is the enthalpy and drag coefficients respectively, T_s is the *SST*, and T_0 is the outflow temperature. h_0^* and h^* are the moist static

energy at the sea surface and the boundary layer. Moreover, the thermodynamic parameters associated with EMPI were further examined such as SST, relative humidity and thermodynamic efficiency. Thermodynamic efficiency is expressed as:

$$\varepsilon = \sqrt{\frac{SST - T_0}{T_0}}$$

The 6 hourly and monthly climatological variables used to calculate EMPI, thermodynamic efficiency and vertical wind shear are SST, sea level pressure, vertical pressure level profiles of temperature, relative humidity and wind vectors were obtained from the ERA5 global reanalysis (Hersbach et al. 2020) dataset (1982-2015) with a spatial resolution of 0.25°. A linear regression equation has been fitted between vertical wind shear and EMPI to assess the influence of vertical wind shear on EMPI. A modified version of EMPI named as Modified maximum Potential intensity (MMPI) has been introduced incorporating the influence of vertical wind shear. A comparative examination was also performed to assess the performance of MMPI estimating maximum intensity of TCs.

The results of this chapter suggested that the EMPI failed to explain the spatial distribution of TC formation locations specifically during the SW monsoon. The mean EMPI during SW monsoon significantly lower compared to post-monsoon. The lower EMPI during SW monsoon was mainly attributed to increased lower tropospheric relative humidity compared to the post-monsoon. TCs were able to achieve 50.06% of their estimated EMPI and only 12.82% TCs reached more than 80% of their respective EMPIs. TCs reached >50% of their EMPI when vertical wind shear was <14.42 m s^{-1} and >90% of their EMPI during vertical wind shear was <6.19 m s^{-1}. MMPI rectified the observed discrepancy between spatial distribution of EMPI and TC formation locations during the SW monsoon. Furthermore, MMPI more efficiently portrayed TC formation locations during the post-monsoon. The absolute difference between observed TC peak intensity and EMPI was 48.47, whereas, the mean difference was reduced at 4.6 kts with the MMPI. TCs were able to achieve 98.66% of their estimated MMPI.

5. **Current trends in TC intensity parameters and evaluation of EMPI for future projected climates**

This chapter focused on the fourth objective. It focused on the assessment of recent trends in TC intensity parameters such as Power Dissipation Index (PDI), EMPI and Lifetime

Maximum Intensity (LMI). Furthermore, it also assessed the EMPI model under the both present and future projected climates. The MK test and Sen's slope has been used to measure the observed direction and magnitude of trend in TC intensity parameters. ERA5 datasets have been used to calculate the EMPI under the present climate. The EMPI was further examined under future projected simulations from CMIP6 climate projections under the SSP5-8.5 emission scenario. The timespan between 2001-2020, 2041-2060 and 2081-2100 represented the present, near- and far-future climates respectively. Moreover, EMPI associated thermodynamic parameters such as SST, thermodynamic efficiency, mixing ratio, dry static stability was also assessed.

The results of this chapter showed no significant trend for PDI and LMI. However, the EMPI showed a significant positive trend with a *z* value of 2.43 and a Sen's slope value of 0.04. EMPI showed no statistically significant change despite of significant increase (0.57° C) in the SST in the near-future climates. The positive feedback of increased SST on EMPI was found to be compensated by an increased mixing ratio (1.17 g/kg) and dry static stability (1.27 K) for the near future climate. The changes in thermodynamic efficiency were found to be not significant. Similar kinds of estimates were found for the far future climate which also showed no statistically significant change in EMPI compared to the present climate. The far future climate was characterized by a significant increase (1.90°C) increase in the SST and despite the increased SST, the EMPI was not significantly changed. The far future climate was characterized by a significant increase in mixing ratio (2.67 g/kg) at 1000 hPa and a significantly higher degree of atmospheric stabilization (4.70 K), which leads to reduce in upward mass flux and makes up for the increased SST. Changes in thermodynamic efficiency was found to be not significant.

6. Simulating TCs under changing climates

This chapter dealt with the fifth objective. It conducted simulation of TCs using a numerical model under different climatic conditions. The Weather Research and Forecasting (WRF) is a numerical mesoscale model which can be used for atmospheric research and operational forecasting purposes. Advanced Research WRF (ARW) is a subset of WRF model supporting ARW dynamic solver along with several compatible components to generate climate simulations. The ARW has been used to simulate idealized TCs under present and CMIP6 projected climate to model kinematic and thermodynamic structures such as surface winds, rain fall, heat fluxes etc. to assess the possible changes due to a probable global warming

scenario. The model incorporated two domains with 200 × 20 grids and resolution of 9 and 3 km. A TC-like vortex was inserted at the middle of the inner domain with intensity of 25 m/s and simulated for 240 hrs. The results of this chapter showed a reduction of 9.05% and 29.97% in maximum surface winds in the near- and far-future climates respectively, whereas, the average wind speed was increased by 5% in the near-future and decreased by 9.32% in the far-future climate compared to the present climate. The average precipitation was found to be increased by 17.01%, for the near-future, whereas, the far-future was accounted for a reduction in average precipitation of 4.65%. The future climate TCs were characterized by cooler core temperature, lower vertical velocity, and higher outflow temperature compared to the present climate. The reduced intensity in the far-future mainly attributed to reduced average latent heat (15.98%) and peak sensible heat (61.95%) flux. The near-future climate was characterized by higher average latent heat flux (11.82%) although peak latent heat flux slightly decreased (1.18%). The peak sensible heat flux was decreased by 4.53%.

7. Summery and conclusion

This chapter summarized all the findings of the entire research work. Significant seasonal variability was observed both in terms of the large-scale environmental factors and the TC genesis patterns over the BoB. TC genesis during the monsoon was greatly reduced due to increased vertical wind shear, whereas, TCs were more intensified due to lower vertical wind shear and increased relative voracity during the post-monsoon despite of lower SST and instability compared to the monsoon. The TC tracks were found to be well associated with surrounding winds at 200 hPa level. The recurving TCs were found to be the result of penetration of TCs in the mid-latitude westerlies. The vertical wind shear was found to be caused for about 50% reduction of the observed maximum intensity of TCs with respect to their EMPI and inclusion of dynamic factors such as vertical wind shear significantly increased the EMPI of TCs. The trend analysis of different TC intensity parameters such as PDI and LMI showed no significant trend, however, EMPI showed a significant Sen's slope value of 0.04. No significant changes in EMPI were observed under the both near- and far-future climate compared to the present. The increased SST was found to be counterbalanced by increased dry static stability and near-surface moisture content in the future climates. The numerical simulation of TCs showed a decrease in maximum intensity under the both near- and far-future climates. The near-future was characterized by increased precipitation, whereas, precipitation was decreased for the far-future. The both future climates showed marked increase in tropospheric stabilization. The static stability was increased by 1.29K and

3.99K for the near- and far-future climates respectively. Changes in the surface heat fluxes and tropospheric stabilization found to be linked with the observed nature of the simulated TCs under the future climates.

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